Presentation

REVALIDATION OF HUYGENS THERMAL BEHAVIOUR DURING TITAN ENTRY

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ABSTRACT

Following the HUYGENS Delta Flight Acceptance Review held in January 2004, a working group was created on the aerothermal environment in order to confirm the heat flux supported by the probe during its entry on Titan with a comparison of the different proposed evaluation methodologies. The working group first iteration has proposed an aerothermal heat flux much higher than the level considered some years before during the probe definition.
The HUYGENS probe thermal behaviour was reassessed considering this environment. Three major difficulties were issued: Thermal Protection System (TPS) qualification, Frontshield and back cover structure mechanical capabilities at high temperature. And the conclusion at the end of this analysis was the non compliance of the probe with the proposed environment.
Meanwhile, the activities on heat flux evaluation were continued.
The further iteration on heat flux evaluation, with the support of the thermal behaviour reassessment has allowed concluding for a go-ahead for the mission in end of 2004.

1. INTRODUCTION

The HUYGENS probe was designed and build between 1991 and 1996, and launch on board of CASSINI in October 15^{th} 1997 from Kennedy Space Centre.
The improvement on TITAN knowledge since the probe development phase has led to an overall verification of the probe performances in 2003. This verification ended by a Delta Flight Acceptance Review, held in January 2004 [1].
The review has allowed confrontation in methodologies for heat flux evaluation [1]. These methodologies have shown a large range of thermal environment prediction for the HUYGENS entry.
ESA has hence created an aerothermal working group to reconcile the different methodologies [6]. Its aim was to support the ESA-ALCATEL SPACE project team in the establishment of a viable mission scenario.
The different partners involved in this working group, ESA [4], NASA [3], EADS-ST which was in charge of the aerothermal environment definition during the probe development [2], and the EM2C laboratory [4], had hectic activities all over the year 2004. The first iteration was issued in June 2004 and the environment level considered for the probe sizing was largely exceeded.
This result has led to 3 actions within the HUYGENS project:

- Continue the activity on heat flux evaluation [2,3,4,6];
- Evaluate the impact of such environment on the probe, subject of the present article;
- Following this first evaluation, re-visit the Thermal Protection System (TPS) qualification and manufacturing [5].

The paper will present the logic followed for the increased heat flux impact evaluation on the probe, and consecutive first conclusions.

2. HUYGENS PROBE DESIGN AND MISSION

The HUYGENS probe was designed to perform Titan atmosphere in situ measurements. The major part of the mission occurred under parachutes.
Once separated from the CASSINI vessel, HUYGENS had a 22 days coast phase before reaching Titan at about 6km/s. The probe was woke-up 4.5 hours before entering in the atmosphere [9].
During the entry phase, where the major velocity decrease was performed, between 6 km/s to 400m/s, the probe is protected from the aerothermal flux by an aeroshell. Titan atmosphere chemical composition includes predominantly methane and nitrogen. Chemical reactions occurring during the entry between the bow shock and the probe have created components that had thermal radiation emission. This thermal flux was thus superimposed to the convective aerothermal flux.

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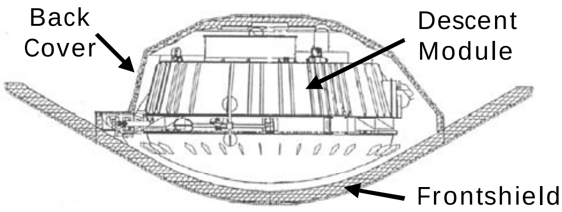

Fig. 1 The HUYGENS probe

Around Mach 1.5, the probe became unstable and 2 parachutes were deployed. The pilot chute was first deployed in order to remove the back cover from the probe. Then the main chute was deployed to reduce the probe velocity through the transonic. The Frontshield was then released and all the instruments were could operate.
The scientific mission has started.

A complete description of the HUYGENS design can be found in [8], and the mission is presented in [9].

3. VERIFICATION METHODOLOGY

3.1 General methodology

Atmospheric entry heat flux is a short transient extremely stressful environment for a probe. TPS materials is designed to allow the high heat rate not to enter into the probe.
The modelling of such TPS material is complex and non-linear as it has to consider complex phenomenon's:

- Conduction heat exchange
- Chemical decomposition
- Phase change of potentially several material

It requires an important discretisation across the TPS thickness. This leads to consider only 1D modelling for TPS behaviour analysis. Such modelling is generally sufficient as the longitudinal conduction can be neglected considering the extreme environment and the poor thermal conductance of such material. However, modern tools allow 2D local modelling to be used for high curvature areas.

Analysis of probe overall thermal behaviour is mandatory to be 3D, considering the high efficiency of thermal path in such vehicle, conductively via the aluminium structure, or radiatively in the enclosures.
The 2 modellings are thus not compatible. Analyses are thus split in 2 parts:

- TPS and substructure analyses on Aeroshell several focal points.
- Classical thermal analysis on the probe, using the TPS analyses results as boundaries.

If the TPS analyses show that the substructure respects the interface temperature upper level, the analysis is stopped at this level. If the margins are considered as insufficient, the analysis is thus continued at probe level.

3.2 Aeroshell focal points of analysis

The focal points of analysis on the HUYGENS aeroshell has concerned both the Frontshield and the back cover:

- Frontshield stagnation point (Fig. 2): Highest heat flux level and low shear stress
- Frontshield mid-cone (Fig. 2): High heat flux (potentially turbulence) and high shear stress. In addition, this point was significant as the Frontshield structure was submitted to heat flux on both sides.

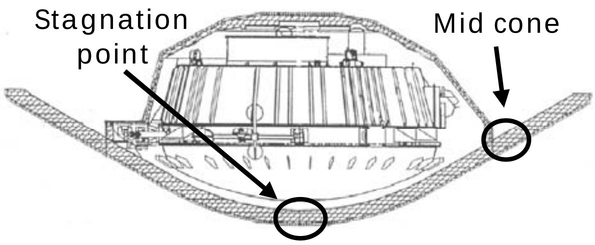

Fig. 2 Frontshield heat flux focal points

On the back cover, the diversity of heat flux level and of TPS thickness has led to a verification of all areas (Fig. 3).

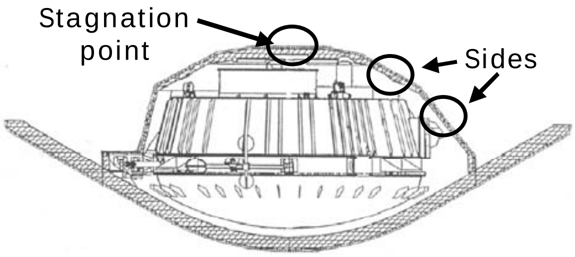

Fig. 3 Back cover heat flux focal points

4. AEROTHERMAL ENVIRONMENT

The first iteration was a first attempt for an independent assessment of entry heat flux on HUYGENS [7]. The activities in this first iteration has highlighted the difficulty in radiative heat flux evaluation in the TITAN atmosphere, which was already the key point during the development phase. This was the major subject of activities during the second 2004 semester in preparation of the mission [2,3,4].

Table 1 presents the Frontshield environment considered for this verification. The back cover heat flux follows the same trend.

Table 1. Frontshield environment

	Peak Heat flux (kW/m²)	Heat loads (MJ/m²)
Stagnation point		
Shallow entry	1057	44
Steep entry	2046	40
Shallow entry 1992	920	36
Mid cone		
Shallow entry	882	34
Steep entry	2305	37
Shallow entry 1992	723	26

The proposed environment shows an increase of more than 20% of the total heat load on the trajectory compared to value used during the design phase.

It was thus verified that the shallow entry was still the sizing case for the TPS. In particular on the mid cone position, even if the submitted heat load is higher on the steep entry than on the shallow one, the heat load effectively entering the TPS is higher on the shallow entry (lower TPS surface self radiative rejection). This leads to higher temperature on the structure (Fig. 4).

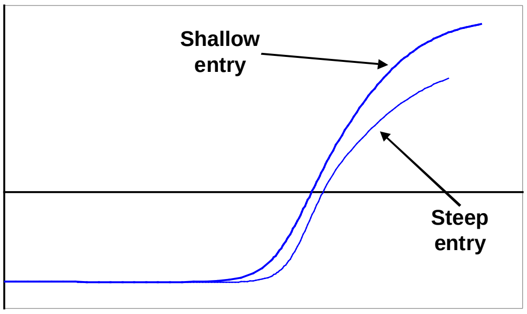

Fig. 4 Frontshield mid cone structure temperature evolution versus time along the entry

5. TPS ANALYSIS

5.1 Frontshield TPS analysis

The specification for the Frontshield TPS was to guarantee the CFRP structure temperature to stay below 180°C. This interface temperature was then used for the Frontshield structure development and qualification. This temperature level was chosen as being the upper level of available experience at this time for CFRP. The feared event in case of high temperature was a Carbon skin / honeycomb glue potential phase change. The bonding could become liquid and thus loose all mechanical properties during this critical phase. This specification was applied at Frontshield end of mission, at its separation from the probe, under the main parachute.

Stagnation point

The analysis conducted by EADS-ST on the stagnation point has shown a structure maximum computed temperature of 143°C, which has provided 37°C of margins.

This level of margins is mainly provided by the TPS low susceptibility to heat flux variation at high level. The efficient isolating Pyrolisis and ablation phenomenon's are already acting. An increase of heat flux, within the same overall time schedule, had thus a moderate impact.

This margin was considered as sufficient to cover necessary uncertainties.

Mid cone

The analysis performed on the mid cone has shown a maximum structure computed temperature reaching 196°C. This level was above the specification and did not account for any uncertainties.

This result is a conjunction of 2 phenomenon's:

- Large increase of the environment load (more than 30% on total heat load, Table 1)
- Large sensitivity of the back face TPS to heat flux variation.

Actually, the heat flux on the back face is of only few percent of the stagnation point level. TPS temperature remains low, thus pyrolisis process is not activated. The insulation is provided by the low conductivity of the TPS material. The insulation varies then almost linearly with the heat flux.

The increase in the environment load stresses the TPS, and has an important impact on the structure.

Such high Frontshield structure temperature was not considered as acceptable and has required deeper analyses.

5.2 Back cover TPS analysis

The back cover structure was a single aluminium metallic foil. Its highest allowable temperature during the entry was defined as 250°C.

The TPS thickness was adapted to the heat flux level distribution on the back cover.

The TPS thermal behaviour simulations have shown sufficient margins on the different areas except on the back cover sides, with a peak computed temperature of 255°C.

The reason for reaching high temperature level was identical to the Frontshield back face one, with a high susceptibility of TPS to variation of environment at low heat flux level.

5.3 Status of the TPS analysis

At this level of the analysis, the project was in front of 3 difficulties, 4 months before the expected date for release of the probe from CASSINI:

- At Frontshield level: TPS qualification (tiles, glue and joints), and CFRP structure
- At back cover level: TPS qualification and structure behaviour at high temperature
- At Descent Module (DM) level: as the back cover interface temperature was above the level considered for the probe sizing

A verification of each probe element capabilities was thus necessary.

6. REVALIDATION OF PROBE THERMAL BEHAVIOUR

6.1 TPS qualification

The difficulty identified in the TPS analysis has concerned the Frontshield cone. In this area, the TPS had to withstand a combination of high heat flux and high shear stress. The development phase has demonstrated the good TPS behaviour in the probe flight range via arcjet tests. Fig. 5 shows a sketch of both the range of tests and the flight domain as evaluated during the development phase [5].

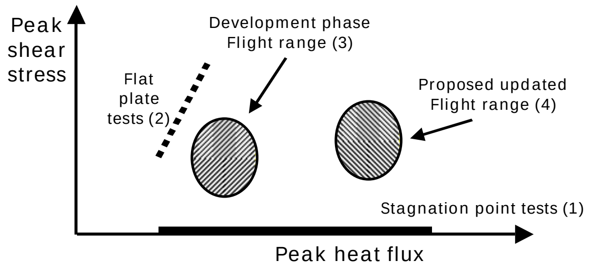

Fig. 5 TPS qualification range

Tests were performed on stagnation point configuration (1 in Fig. 5), up to level largely higher than the flight ones [5]. Tests in flat plate configurations (2 in Fig. 5), which combine heat flux and shear stress, were driven by facility limitation. At that time, the demonstration was considered as acquired (area 3 in Fig. 5).
When submitted to heat flux, a char layer is created on the TPS external side. This porous low conductance material has a weak mechanical strength but is of major importance for the thermal insulation. The feared events related to TPS qualification was a removal of this char layer by the boundary layer shear stress, which will induces an even lower thermal insulation capability under higher heat flux.

The proposed environment exceeds largely the tested range (area 4 in Fig. 5).
The very good TPS behaviour at very high flux in the stagnation point configuration has provided engineering confidence in the material capability to withstand the proposed environment. However, this level was too far from the tested range to consider favourably TPS behaviour extrapolation as a demonstration.

6.2 Frontshield structure

The feared event for CFRP structure at high temperature was presented in §5.1. Fig. 6 shows typical CFRP mechanical strength decrease with temperature. The qualification of 180°C leads to characteristics decreases to 80% of room temperature level. Considering the computed 196°C plus necessary margins lead to less than 60% of the room temperature level capabilities.

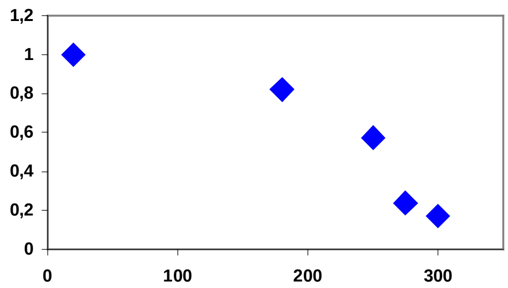

Fig. 6 CFRP mechanical strength decrease with temperature (°C) with regard to room temperature level

During the development phase, worst case was considered for the sandwich qualification and sizing: maximum mechanical load combined with highest temperature.
Such hypothesis has led to negative margins on mechanical sizing with the proposed environment.
It was thus necessary to review the Frontshield mission and to verify in each case the mechanical/thermal behaviour. Table 2 presents the Frontshield mission life.

Table 2 Frontshield mission like

Events	Thermal environment	Mechanical environment
Entry Interface Point	Cold level (-80°C)	No loads
Peak deceleration	Moderate level (<100°C)	Peak pressure effect on the Structure (~13 kPa, ~58kN)
Pilot chute deployment	High temperature	Moderate load (~2kN)
Main chute deployment	High temperature	Moderate load (~15kN)
Frontshield separation (end of mission)	Maximum temperature	No loads (only weight)

Three events are highlighted in Table 2:

- Peak deceleration: This event is covered by the development phase qualification
- Main chute deployment: This last mechanical load on the Frontshield before the end of mission is the significant event. The maximum structure temperature was computed to be about 175°C at this time, which, combined with the mechanical loads provides a safety margin higher than 3. However, the data used for this evaluation were based on only 3 tests, which was not considered as sufficient to state on a qualification.
- Frontshield separation: No mechanical loads were applied when the highest temperature was reached. This event was thus considered as not critical.

The confidence was very high with regard to the Frontshield mission, as the sizing mechanical load occurs at moderate temperature level, and as large margins exist at the last significant mechanical load with high temperature.

6.3 Back cover structure

The back cover sizing case identified since the probe earlier studies was the pilot chute inflation with both high temperature and the sizing mechanical load.

The critical area was the connection between the 3 pilot chute clevis and the back cover aluminium skin (Fig. 7).

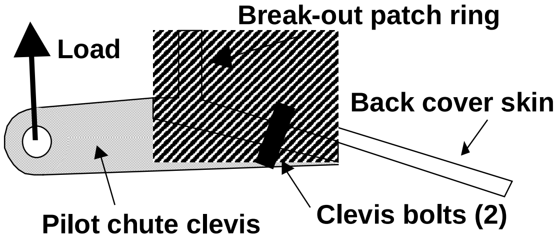

Fig. 7 Pilot chute attachment on the back cover

Aluminium has reduced mechanical strength at high temperature. Data are available from Aircraft experience in terms of temperature level and duration. The major difference between HUYGENS and an Aircraft is that the HUYGENS back cover was at high temperature for less than a minute, compared to cumulated hours for Aircraft flight. The analysis performed in 1995 by CONTRAVES has shown a decrease of the material capability of 23% at 250°C compared to the room temperature performance.

CONTRAVES has performed this analysis again in 2004, using other reference data for material performance, which have shown a decrease of 40% in aluminium performance. The updated analysis using these data has led to negative Safety Margin .

However, the analysis has considered the conservative assumptions of a static mechanical analysis:

- No load redistribution in the back cover
- No probe rotation under the load constraints (all the loads on one clevis and probe considered as clamped in the numerical simulations)

In addition, the analysis was performed considering material elastic behaviour, while back cover plastic deformation could be functionally allowed, as no other function is applicable to this element.

The review of these analysis hypotheses has led the ESA-ALCATEL SPACE project team to be confident in the back cover good behaviour in such conditions, even if it is formally not compliant.

This analysis has pointed a difficulty encountered during all the activities performed since the Delta Flight Acceptance Review preparation: Find all the documents and justifications that were used for the probe design and manufacturing. If it was generally possible to find the necessary information, Aluminium characteristics at high temperature used 10 years ago was not available, and the data used as a substitution has provided worst cases of degradation.

This must be pointed for future mission with long life duration, as for the ESA ROSETTA mission which will starts its scientific mission 10 years after launch.

6.4 Descent Module

The Descent Module thermal design was defined using the back cover interface temperature level of 250°C. The temperature level issued from the TPS analysis has led to verify the Descent Module behaviour.

DM structure and internal elements

The thermal control of the Descent Module structure and internal elements, including experiments, was managed via a global thermal mathematical model. The back cover interface temperature considered for the numerical simulations was in fact higher than the specification. The actual TPS analysis results are covered by the thermal analysis performed during the probe development.

DM external elements

Concerning the Descent Control SubSystem, DCSS, Martin-Baker/VORTICITY has performed an update of the thermal analysis made during the probe development, using the proposed interface temperature. This analysis has presented a compliance with this environment.

A local thermal analysis of the antennas has not shown any criticality.

A similar simple analysis was performed on the separation subsystem critical area: DASSAULT Pyrotechnical device that has an auto-inflammation process at 110°C. In fact, the structure of the pyro and the mechanisms structure thermal inertia protect these elements from critical hot temperature, and they are only slightly affected by the entry heat flux.

No criticality was thus concluded on the Descent Module with regard to the proposed environment.

7. STATUS AT THE END OF THIS ANALYSIS

7.1 Status

Most of the HUYGENS probe elements can withstand higher heat flux than considered for the sizing, but three major difficulties remains:

- TPS qualification : but the engineering feeling remains good considering the TPS good behaviour during tests;
- Frontshield structure : but margins exist with regard to the last significant event;
- Back cover structure : but the analysis was performed considering conservative assumptions.

In order to improve the situation, the only available degree of freedom is the trajectory Flight Path Angle (FPA), which was already modified for the Delta Flight Acceptance Review.

Reduce the FPA to shallow entry will have decrease the peak heat flux and thus relax the difficulty in the TPS qualification. However, it will have increase the total heat loads, thus the structure temperature, and thus worsen the difficulties on the aeroshell structure.

On the opposite, increase the FPA to steep entry will have relax the difficulty in aeroshell temperature but will have worsen the TPS qualification demonstration.

The status at the end of this analysis, four months before the mission, was thus a formal non compliance of HUYGENS with the proposed environment, despite the engineers individual confidence in the probe capabilities, without solution for improvement of the situation.

7.2 Following activities before the flight

In parallel to this study, the activities were continued on both the heat flux evaluation [2, 3, 4] and the TPS behaviour [5].

The thermal analysis presented in this paper has led to a negative result, but has provided all information on the probe limitation that was used in the last month of 2004 to support the Go-ahead for the mission [6].

8. FLIGHT

The HUYGENS mission held on January 14th, 2005 at about 9 a.m. UTC.

Thanks to the high precision separation performed by the CASSINI NASA team, the probe has performed an entry very close to the nominal one.

The probe aeroshell was not carrying technological measurements, as all probe capabilities was devoted to science. It is thus not possible to have a direct information on what was the aerothermal environment during the entry.

The temperature measurements inside the Descent Module were only slightly affected by the entry, not higher than expected.

9. ACKNOWLEDGEMENT

The authors would like to acknowledge EADS-ST, CONTRAVES, MBA / VORTICITY and DASSAULT for their involvement and their team spirit, which has helped the project to have all the information for the success of the HUYGENS mission.

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